The Origin of Cosmic Rays and the Diffuse Galactic Gamma-Ray Emission

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Abstract. Cosmic-ray interactions with interstellar gas and photons produce diffuse gamma-ray emission. In this talk we will review the current understanding of this diffuse emission and its relationship to the problem of the origin of cosmic rays. We will discuss the open issues and what progress might be possible with GLAST, which is planned for launch in 2006.

1. INTRODUCTION

The problem of the origin of cosmic rays (CRs) has existed for almost a century. In 1912, Victor Hess carried an electroscope aloft in a hot air balloon and discovered radiation increasing with altitude and exhibiting no day-night variation. It had to be some kind of highly-penetrating radiation coming from beyond the solar system. Then in 1948, Freier et al. [1] discovered that this radiation included nuclei of heavy elements with relative abundances similar to the solar system.

Much has been learned since about the important dynamical consequences of CRs for the Galaxy [2]. CRs are tied to magnetic fields, magnetic fields are anchored in the gas phase of the Galaxy, and the gas is held in place by gravitational forces. From radio mapping of external spiral galaxies like our own Milky Way, CRs are known to be common to galaxies. Evidence for the shock acceleration of electrons in supernova remnants (SNR) has recently been found (see Sec. 2). However, no convincing evidence has been found for the commonly held view that CR nuclei are also accelerated in SNR. A few percent of the energy released in SNR must find its way into energetic CRs in order to keep the Milky Way galaxy supplied with CRs.

Interactions of CRs with the interstellar medium (ISM) and photons produce diffuse high-energy gamma radiation that is diagnostic of the CRs. The γ-ray fluxes are low, but γ-rays do have the advantages of not being deflected by magnetic fields and low optical depth for attenuation by intervening matter. Results from observations of diffuse γ-ray emission by the Energetic Gamma Ray Experiment Telescope (EGRET) on the

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Compton Gamma Ray Observatory have shown the potential of γ-ray measurements to contribute to solving the problem of the origin of CR nuclei ([3] and references therein).

In this paper we review the current understanding of CR origin and sources, CR diffusion throughout the interstellar medium, and the production of γ-rays by both CR nucleons and electrons. We also review the discoveries of EGRET and explore the problems relating to the interpretation of those results. We document some open questions and discuss how the Gamma Ray Large Area Telescope (GLAST) can contribute.

2. THE ORIGIN OF COSMIC RAYS

Observations of the Magellanic clouds with EGRET have shown that CRs in the GeV range are almost certainly Galactic [4]. However, only a few classes of objects in the Galaxy provide sufficient energy and power to replenish the CRs, one of which is SNR. In fact, particle acceleration at SNR shock waves is regarded as the most probable mechanism for providing CRs at energies below 10^{15} eV.

The distribution of SNR in the Galaxy is so poorly known and the propagation range of CRs, which is related to the halo size, is so weakly constrained, that a comparison of the CR source distribution, which may be inferred from the γ-ray gradient (Sec. 3), with the distribution of SNR must be inconclusive. A direct search for γ-ray emission from SNR is an alternative strategy. In fact, a few unidentified EGRET sources are positionally coincident with radio-bright SNR [5], but similar correlations exist with OB associations and SNR-OB associations (SNOBs) [6], not to mention the possibility of these sources actually being radio-quiet or highly dispersed pulsars. The EGRET data alone do not permit a firm identification of γ-ray sources with SNR, for the angular resolution is too coarse.

TeV observations using the atmospheric Čerenkov technique can be performed with much higher angular resolution and sensitivity than is possible with EGRET. However, the much higher threshold energy implies that CRs with energies around 100 TeV are probed. The most simple calculations of shock acceleration [7] indicate that particle spectra with number index ~ 2 may be produced, but also that acceleration cut-offs have to be expected at 0.1–1 PeV [8]. Corresponding models of hadronic γ-ray emission from SNR have suggested that a number of sources should be detectable with present-day telescopes [9], in particular those embedded in dense gas [10]. Following these expectations, very deep surveys of TeV emission from SNR were performed, but no SNR has been unambiguously detected as a source of hadronic TeV γ-rays to date [11].

More careful models of shock acceleration, which include non-linear effects arising, e.g., from the influence of the accelerated CRs on the shocked plasma, predict particle spectra that deviate from pure power laws [12]. Also, the energy and momentum carried by electromagnetic turbulence and the motion of the CR scattering centers relative to the plasma modify the process of shock acceleration, such that an E^{-2} spectrum is not the canonical result it was thought to be [13]. In fact a distribution of spectral indices should exist, and this is actually observed in the radio spectra of shell-type SNR [14]. Therefore, the non-detection of hadronic TeV emission from SNR may be not incompatible with CR acceleration in these sources; nevertheless, the results seem to conflict with the notion that SNR accelerate CR hadrons up to the “knee” (Sec. 3).

The recent detections of non-thermal X-ray synchrotron radiation from the SNR SN1006 [15], RX J1713.7-3946 [16, 17], IC443 [18], Cas A [19], and RCW86 [20], and the subsequent detections of SN1006 [21] and RX J1713.7-3946 [22] at TeV energies support the hypothesis that at least Galactic CR electrons are accelerated predominantly in SNR. The relative intensities of the keV synchrotron emission and the TeV inverse Compton (ICS) radiation are independent of the acceleration process and the model thereof [23]. Care has to be exercised in separating thermal from non-thermal X-ray emission [24], though, and the substructure of the SNR shock as well as propagation effects have to be taken into account when interpreting the TeV data [25, 26]. Nevertheless SN1006 and RX J1713.7-3946 are obvious examples of leptonic TeV γ-ray emission. The most recently detected SNR, Cas A [27], is a less clear case, but presumably the emission is also of leptonic origin [28].

It is interesting to note that for all SNR the X-ray flux, synchrotron or not, is less than the extrapolated radio synchrotron spectrum. Since many of the sources, in particular the five historical remnants, are too young for their electron spectra to be limited by energy losses, acceleration cut-offs must occur at electron energies of 100 TeV or less [29], which would be intrinsic to the actual acceleration process.

The production of CR electrons in SNR has important consequences. At energies higher than about 100 GeV the lifetime of electrons, and thus their range, is rather short; only a few SNR would contribute to the locally observable CR electron spectrum. Therefore the locally measured spectrum would not be representative of the spectrum elsewhere in the Galaxy. This conclusion is the basis for the ICS models of the GeV excess [30] (Sec. 3).

3. PROPAGATION OF COSMIC RAYS

The spectrum of CRs can be approximately described by a single power law with index –3 from 10 GeV to the highest energies ever detected, $\sim 10^{20}$ eV. The only feature observed is a “knee” around 10^{15} eV. Because of this featureless spectrum, CR production and propagation are believed to be governed by the same mechanism over decades of energy; a single mechanism works below the knee and the same or another one works above the knee, although the origin of the CR spectrum is not still understood.

Energetic CR interactions with gas or magnetic and radiation fields in the interstellar medium produce γ-rays that carry information about these interactions such as the spectrum and flux of CR and physical conditions such as the gas density and radiation field. Some portion of γ-rays is produced near the CR sources, like SNR and pulsars, that generally appear as point sources to γ-ray telescopes. The rest are produced in CR interactions in the ISM and are therefore diffuse.

In the ISM particles diffuse and lose or gain energy, and so their spectra change from their initial forms. Freshly-accelerated particles (Sec. 2) propagate in the ISM where they produce secondary particles and γ-rays. Electrons produce synchrotron photons and γ-rays via ICS and bremsstrahlung. Nucleons spallate and produce secondary nucleons, antiprotons, and charged pions that give rise to secondary positrons and electrons.

Decays of secondary π^0's also produce γ-rays.

CRs can be measured directly only in the solar system, in the outskirts of our Galaxy. Those observed in the solar system are a complicated mixture of primary and secondary particles which are diffusing through the ISM from their sources. Only photons or γ-rays are able to deliver the information directly from other parts of the Milky Way, but this information is integrated over the line of sight. To extract information about CRs from γ-rays models of CR propagation are needed.

CRs propagate throughout the Galaxy guided by magnetic fields. They are held in the Galaxy by scattering on magnetic irregularities, the process described mathematically as diffusive propagation. The models can be complex and distinguish between the diffusion rates in the thin galactic disk and extensive halo [31]. The diffusion coefficient may depend on the local plasma conditions and is probably different in the disk and the halo. It is often assumed to depend on particle rigidity with index 0.33–0.6, with the former value reflecting a "Kolmogorov" spectrum of magnetic scattering centers and the latter obtained phenomenologically from fitting the measured B/C ratio. Propagation may be influenced by a galactic wind (convection of particles away from the Galaxy) and/or diffusive re-acceleration (a second order Fermi process).

The diffusive model can be shown to be equivalent to, and because of the complexities mentioned above is often replaced by, a simpler empirical formalism known as the "leaky-box model." In this model the principal parameter is an effective escape length or grammage (column density of matter traversed, in g cm^{-2}) and the sources and particles are uniformly distributed in space and time throughout the Galaxy. The grammage parameter is determined by fitting to the data and found to be a broken power law in rigidity, increasing at low energies and decreasing with index –0.6 at relativistic energies.

Detailed CR diffusion models have been developed over the last 30 years. The GALPROP model [32], for example, is a recent numerical model which combines the Galactic structure with diffusive reacceleration and convection in the ISM. This model incorporates all CR species with $Z < 29$ including leptons and antiprotons, together with γ-rays and synchrotron emission.

Measurements of primary CR abundances or stable secondary/primary ratios do not permit distinguishing between the leaky box and diffusion models. However, the propagation of radioactive secondary isotopes depends on the lengths of time that particles spend in the disk (production) and the halo (decay), therefore making them sensitive probes of the propagation model.

Propagation parameters are usually derived using B/C and (Sc+Ti+V)/Fe ratios, while radioactive secondary isotopes ^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn (all with $T_{1/2} \sim 0.3$–2 Myr) allow the size of the halo to be constrained. Figure 1 shows examples of B/C calculations and halo size constraints derived from radioactive isotopes [33]. Once defined from B/C and Be measurements, the propagation parameters determine other isotopic ratios.

Typical values of the diffusion coefficients depend on the propagation model and values of cross sections employed, but all of them are of the order of few times 10^{28} cm^2 s^{-1}. Larger values make the propagation more rapid and produce smaller amounts of secondaries, smaller values increase the secondary/primary ratios.

The spectrum of diffuse γ-rays from the inner Galaxy has excesses at high and low energies compared to calculations based on the assumption that the nucleon and electron spectra do not change shape throughout the Galaxy [39, 40] (see Sec. 4 and Fig. 3). This

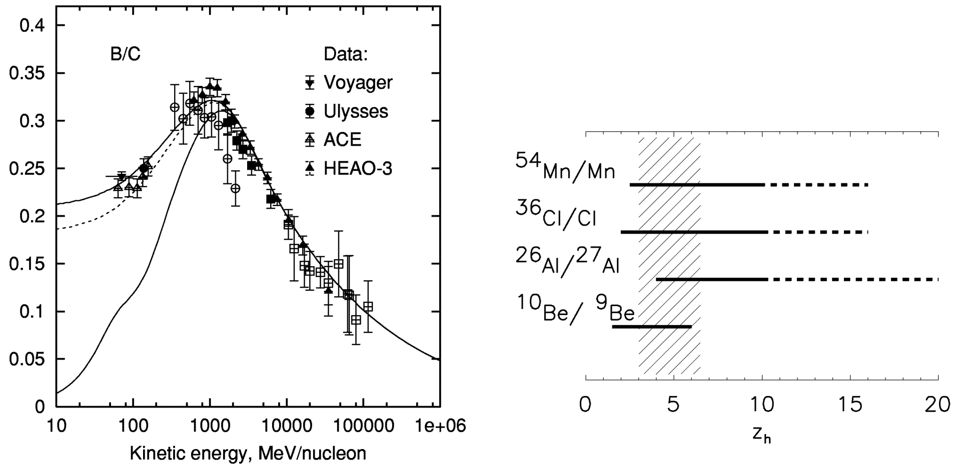

FIGURE 1. **Left:** B/C ratio calculated for CR halo scale height $z_h = 4$ kpc [33]. Lower curve local interstellar spectrum, upper modulated: solid curve – $\Phi = 500$ MV, dotted curve – 400 MV. Data below 200 MeV/nucleon: ACE [34], Ulysses [35], Voyager [36]; high energy data: HEAO-3 [37], for other references see [38]. **Right:** Halo size limits [33] derived from the abundances of the 4 radioactive isotopes and ACE data. The ranges reflect errors in ratio measurements, source abundances, and production cross sections. Dashed lines indicate uncertain upper limits. The shaded area indicates the range consistent with all ratios.

implies that the local spectra may be not representative for the Galaxy as a whole. At low energies, the excess may be due to unresolved point sources that dominate in the MeV range and below [41]. At high energies, where most photons come from ICS and π^0 decay, the excess can be explained by spectra of nucleonic [42] and/or leptonic [30] components that are harder than those observed locally.

Secondary antiprotons and positrons are produced in the same nucleonic interactions in the ISM as π^0's and thus provide information complimentary to that of γ-rays (without direction information), but in this case the agreement is good [40]. The leptonic hypothesis of the origin of the excess at high energies therefore may be more plausible, especially because of large energy losses of high energy electrons.

A new test for the origin of the excess will be feasible with the new generation telescope GLAST (Sec. 5), which will be able to measure γ-rays up to 300 GeV for the first time. While improved angular resolution will allow better discrimination of the point source contribution, the capability for spectral measurements at sub-TeV energies is essential to distinguish between diffuse nucleonic and ICS spectral components. The shape of the γ-ray spectrum from π^0-decay resembles the spectrum of the nucleonic component of CRs; the ICS spectrum is flatter and its cut off energy is determined by the maximum energy to which SNR can accelerate electrons. Because this energy is in the 1–100 TeV range, the spectrum of γ-rays in the 10–100 GeV range is therefore crucial [43].

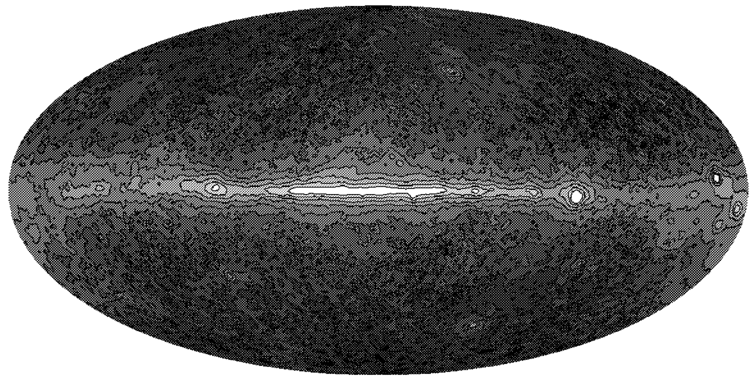

FIGURE 2. Intensity of gamma rays (> 100 MeV) observed by EGRET. The broad, intense band near the equator is interstellar emission from the Milky Way. The intensity scale ranges from 1×10^{-5} cm^{-2} s^{-1} sr^{-1} to 5×10^{-4} cm^{-2} s^{-1} sr^{-1} in ten logarithmic steps. The data have been smoothed slightly by convolution with a gaussian of FWHM 1.5°.

4. RESULTS AND QUESTIONS FROM EGRET

EGRET completed the first all-sky survey at high-energies (> 30 MeV, Fig. 2). More than 60% of the γ-rays that EGRET detected are from CR interactions in the Milky Way. The sensitivity as well as the excellent background rejection of EGRET enabled great progress in the study of interstellar γ-ray emission.

EGRET observations of the Large and Small Magellanic clouds confirmed that CRs are galactic in origin, rather than metagalactic or universal. The γ-ray flux of the LMC measured by EGRET is consistent with a CR density similar to that in the Milky Way [44]. However, the upper limit measured by EGRET for the SMC implies a CR density several times less [4].

The EGRET γ-ray spectrum of the inner Milky Way (Fig. 3) provided the first clear evidence for both electron and proton CRs across the Galaxy, with the spectrum following the π^0 "shoulder" for energies greater than the proton emissivity peak at half the π^0 rest mass [39]. Above $\sim$ 100 MeV, π^0 decay γ-rays from proton-nucleon interactions are the dominant spectral component. At lower energies the spectrum is dominated by electron interactions via bremsstrahlung and ICS.

Models of the interstellar gamma-ray emission of the Milky Way based on the known γ-ray production mechanisms, together with inferred distributions of interstellar gas, low-energy photons, and CRs, predict γ-ray intensities consistent with the observations on scales of degrees [45, 39, 30, 40]. Owing to the limited statistics and angular resolution of the data, such models are essential for determining accurate positions and fluxes of γ-ray point sources at low latitudes. They are also the means to discover the distribution of CRs in the Milky Way. Broadly speaking, the CR distributions derived from the models are consistent with each other. However, differences in approach, including techniques used to resolve the non-unique inversion of radio and millimeter spectral line surveys into the 3-dimensional distribution of gas, presently limit the usefulness of detailed comparisons between models.

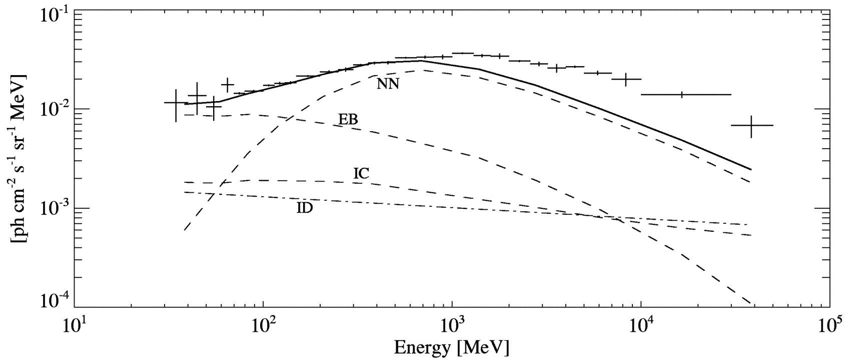

FIGURE 3. Spectrum of the inner Milky Way ($|l| < 60°$, $|b| < 10°$) with calculated components from bremsstrahlung (EB), inverse Compton (IC), π^0 decay (NN), and extragalactic isotropic emission (ID) [39].

For the nearest interstellar clouds, EGRET provided linear resolutions of ~ 10 pc. Studies of these, e.g. [46], permit the tightest direct constraints on confusion of unresolved gamma-ray point sources with diffuse emission, and also on the assumptions that CR densities and the molecular mass calibration, i.e., the relation of 2.6 mm CO line intensity W_{CO} to $N(H_2)$, are uniform on the scale of interstellar clouds.

The GeV excess (see Sec. 3) is evident in Fig. 3, as well as in spectra for smaller angular scales. Several explanations of the excess emission are possible: EGRET calibration error, uncertainty in the π^0 production, unresolved hard point sources, and a Galactic average proton and/or electron spectrum that may be harder than observed locally. An explanation involving ICS from electrons is perhaps the most plausible (see Sec. 3). Calibration error is unlikely, as the observed spectra of EGRET point sources, which are generally well described by single power laws, do not harden above 1 GeV (e.g., [47]). The π^0 production function has recently been re-evaluated using nuclear interaction Monte Carlo codes, and the hardening of emissivity predicted at GeV energies is not sufficient to explain the GeV excess [48]. Hunter et al. [39] concluded from the shape of the spectrum of the inner Galaxy that the contribution from unresolved sources with power-law spectra is $< 10\%$. This estimate is, however, rather uncertain because a large contribution from unresolved sources distributed closely like the molecular gas – although not evident in studies of local clouds – could be accounted for by reducing the $N(H_2)/W_{CO}$ ratio. Pulsars not detected individually could contribute significantly above 1 GeV, although apparently not with the correct latitude distribution [49, 50].

A halo of high-energy (> 100 MeV) γ-rays about the Milky Way remains when the EGRET team's interstellar emission model is subtracted from the observations [51, 52]. The simplest interpretation for the halo is incomplete accounting of the ICS emission at high latitudes (e.g., [53]). Other interpretations based on CR interactions in the halo with very cold H_2 in dense clumps, a dark matter candidate, have been proposed (e.g., [54]). The ICS interpretation alone appears sufficient. EGRET data may in fact offer little insights about baryonic dark matter in the halo. Even if the dark matter is in dense clumps, they could be dense enough to attenuate any γ-rays produced in them [55].

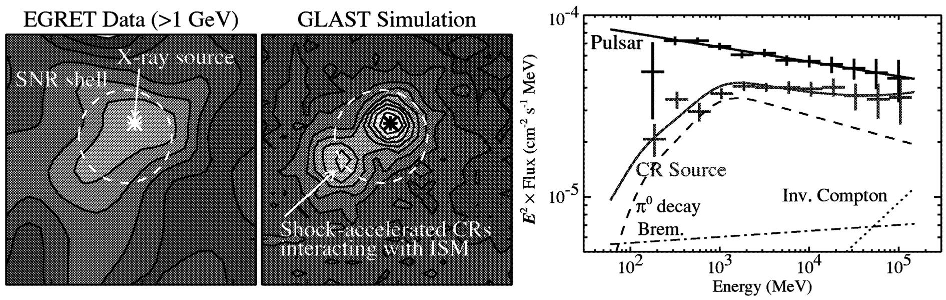

FIGURE 4. EGRET observation (summed Phase 1–4) and GLAST simulation (1-year sky survey) of the γ-Cygni SNR. The dashed circle is the location of the shell [58]. The spacing of the tick marks is 1 °. Also shown are simulated measurements with GLAST of the spectra of the pulsar and CR source. See text for discussion of the γ-Cygni model.

5. ADVANCES ANTICIPATED WITH GLAST

The general capabilities of the Large Area Telescope on the Gamma-ray Large Area Space Telescope (GLAST), which is planned for launch in 2006, are described elsewhere in this volume [56]. The advantages of the large effective area, high observing efficiency, and narrow point-spread function of GLAST for the study of CR production and diffuse γ-ray emission are considered here.

Supernova remnants have been established as acceleration sites of leptons, but the acceleration of hadrons has not yet been detected (Sec. 2). The observational signature of proton acceleration would be expected to be π^0-decay γ-ray emission from proton collisions with nucleons in interstellar clouds being overtaken by SNR shocks. The γ-ray spectrum would appropriately reflect the hard spectrum of the CRs.

Although several EGRET γ-ray sources are spatially coincident with SNR [5, 57], the large positional uncertainties for the EGRET sources and the limited photon statistics do not permit π^0-decay emission from the shell to be distinguished from leptonic emission processes, or even from γ-ray emission from associated pulsars.

The potential for GLAST to clarify the nature of the associations is illustrated in Figure 4, which shows EGRET data and a GLAST simulation for the γ-Cygni SNR. This region was detected as a point source by EGRET (and designated as 3EG J2020+4017 [59]). An X-ray source at the position indicated in the figure has the spectral characteristics of a pulsar and has been proposed as the counterpart to the EGRET source [60]. For the simulation, it was assumed that the flux could be divided 60%/40% between the prospective pulsar and a source at the shell of the SNR where the EGRET data suggest an extension. Spectra for the two sources were selected to be consistent with the overall spectrum of 3EG J2020+4017 and the spectral components of the shell source were chosen to be consistent with models of the γ-ray emissivity of SNR [61] (for details see [62]). The GLAST intensity map shows that the CR source will be resolved from the pulsar at high energies. In addition, the spectra of the sources will be separately measurable at energies above 150 MeV, and the π^0-decay component of the shell source will be strongly detected.

For the study CRs in the Milky Way, the superior effective area and angular resolution of GLAST will permit important advances. GLAST will reveal whether unresolved (by EGRET) point sources are only a minor component of the celestial γ-ray flux, as is currently suspected (Sec. 4; [39]). The angular resolution of GLAST also will be important for studying the coupling of CRs to the spiral arms in the inner Milky Way. The diffuse interstellar emission is intense and quite structured near the Galactic equator, and evidence for coupling will require careful separation of components at different distances, most likely by study of the emission near the tangent directions of the arms.

GLAST observations of interstellar clouds at GeV energies may permit a new test of the origin of the GeV excess. CR electrons fully penetrate molecular clouds and produce γ-rays via bremsstrahlung and ICS with low-energy (microwave to ultraviolet) photons within the cloud. The radiation field inside a cloud varies with visual extinction to its center: the ultraviolet and optical radiation intensities decrease rapidly with increasing depth whereas the far-infrared radiation is ~ 10 times more intense throughout the cloud than the Galactic interstellar radiation field [63]. The resulting variation of the gamma-ray spectrum across the face of a cloud could be used to determine the ICS component.

GLAST will map the interstellar γ-ray emission of the LMC, SMC, and possibly M31, and additionally will likely detect several other local group galaxies and starburst galaxies as point sources, greatly expanding the potential for high-energy γ-ray studies of CRs.

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